

Consolidated SVPWM for Single-Phase Fault-Tolerant Control of CFNI-Based Inverter

Research paper

Meriam Miraoui^{1,*}, Mohammed Larbi Elfahyani¹, Asmae Miraoui², Hana Zekraoui¹

¹LGEM Laboratory, Higher School of Technology, Mohammed First University, Oujda, Morocco

²ESETI Laboratory, National School of Applied Sciences, Mohammed First University, Oujda, Morocco

Received: 4 June, 2026; Received in the revised form: 1 September, 2026; Accepted: 9 September, 2026

Abstract: Fault-tolerant control is essential for traction drive systems, which are pivotal components in electric vehicles and high-dependability applications. These systems face significant challenges, particularly under single-phase faulty conditions at either the machine or the inverter level, which can lead to performance degradation or system failure if not properly managed. This paper presents a fault-tolerant approach based on a consolidated space vector pulse width modulation (SVPWM) to enable the traction drive system to operate under single-phase faults. The proposed method leverages the capacitor-based four-leg neutral-point-connected inverter (CFNI) topology and integrates a remedial approach grounded in field-oriented control (FOC) to drive a permanent magnet synchronous motor (PMSM). The simulation results validate the effectiveness of the proposed method in maintaining reliable operation under fault conditions, preserving accurate speed and torque tracking with minimal deviations. Nevertheless, the elevated current stress observed during fault scenarios requires oversized inverter ratings. These findings demonstrate the robustness of the proposed SVPWM strategy implemented on the CFNI topology, confirming its viability for single-phase fault-tolerant traction drive applications.

Keywords: *fault-tolerant control • space vector pulse width modulation • capacitor-based four-leg neutral-point-connected inverter • permanent magnet synchronous motor • field-oriented-control*

1. Introduction

Fault-tolerant control has emerged as a fundamental requirement in traction drive systems (Orlowska-Kowalska et al., 2022), representing vital components in electric vehicles and other high-dependability applications. These systems incorporate various subsystems, such as inverters, sensors, motors and control units, to ensure efficient, uninterrupted operation.

Modern fault-tolerant control (FTC) systems for electrical vehicles (EV) traction drives typically combine three coordinated stages: fault detection and diagnosis (FDD), fault isolation, and control reconfiguration. Over the past decade, significant research efforts have been devoted to the development of advanced FDD and FTC strategies for various fault scenarios in electric drives (Ahmed Baba et al., 2023; Bhuiyan et al., 2020; Gherghina et al., 2025; Khaneghah et al., 2023; Kumar et al., 2025; Li et al., 2025; Orlowska-Kowalska et al., 2022; Romdhane et al., 2026a,b). For instance, several studies have addressed inter-turn short-circuit (ITSC) faults in permanent magnet synchronous motors (PMSMs) using model-based, signal-based, and artificial intelligence techniques (Orlowska-Kowalska et al., 2022; Romdhane et al., 2026a,b; Zerdani et al., 2022; Zhang et al., 2025, 2023). Current, speed, and position sensor faults, including offset, gain, and complete signal loss, have also received considerable attention, with active FTC approaches based on observers, adaptive estimation, and neural networks (Adamczyk and Orlowska-Kowalska, 2023; Kommuri et al., 2016; Orlowska-Kowalska et al., 2022; Teler, 2026; Yousfi et al., 2009). Likewise, numerous contributions have focused on inverter switch faults, through fast detection algorithms

* Email: miraoui.meriam@gmail.com

and control reconfiguration methods (Altin et al., 2018; Bianchi et al., 2003a; De Araujo Ribeiro et al., 2004; Elsayed et al., 2022; Estima and Cardoso, 2012; Fadil et al., 2018; Hicham et al., 2017; Miraoui, 2025; Orlowska-Kowalska et al., 2022; Zerdani et al., 2019, 2021; Zhiduan and Lihao, 2024b). These studies demonstrate the growing interest in enhancing the reliability and availability of traction drive systems under a wide range of fault conditions.

The present study focuses on single-phase faults in drive systems, including loss of a phase-current measurement, failure of an inverter phase leg and loss of one motor phase. Once the faulty phase is identified and isolated, continued operation requires an alternative current path with an appropriate post-fault control strategy. Therefore, the converter topology plays a decisive role in determining the achievable performance under degraded operating conditions.

1.1. State of the art

Several fault-tolerant inverter configurations have been proposed to maintain the operation of electric drives after a single-phase fault (Mirafzal, 2014; Tousizadeh et al., 2019; Welchko et al., 2004; Zhang et al., 2021, 2014). Among the representative configurations reported in the literature are the switched-based four-leg inverter (SFI; Figure 1a), the capacitor-based four-leg inverter (CFI; Figure 1b), the switched-based four-leg neutral-point-connected inverter (SFNI; Figure 1c), and the capacitor-based four-leg neutral-point-connected inverter (CFNI; Figure 1d).

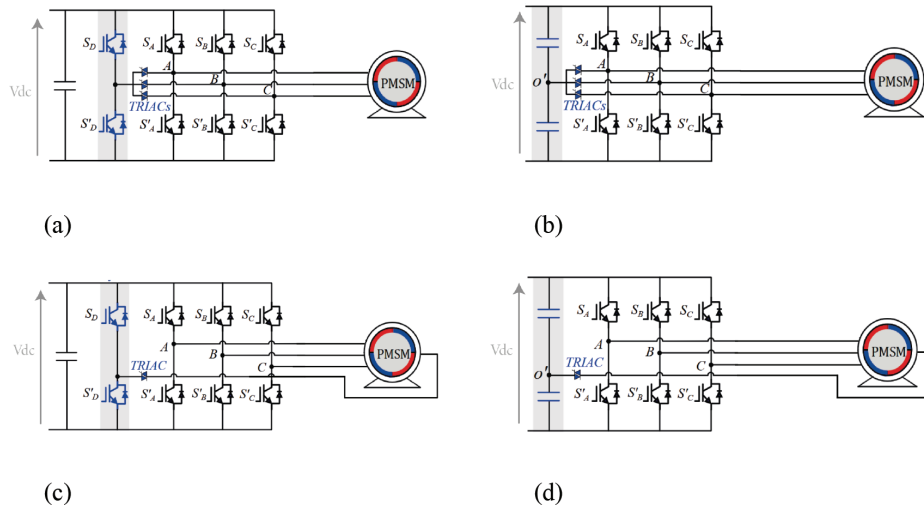


Figure 1. Schematic of three-phase fault-tolerant topologies. (a) SFI. (b) CFI. (c) SFNI. (d) CFNI. CFI, capacitor-based four-leg inverter; CFNI, capacitor-based four-leg neutral-point-connected inverter; SFI, switched-based four-leg inverter; SFNI, switched-based four-leg neutral-point-connected inverter.

CFI topology has been extensively investigated for fault-tolerant operation (Fadil et al., 2018; Hang et al., 2023; Hicham et al., 2017; Huang et al., 2021; Hu et al., 2021; Li et al., 2019; Zerdani et al., 2019, 2021; Zhiduan and Lihao, 2024a; Zhu et al., 2017), whereas SFNI has been considered in previous fault-tolerant drive studies (Bianchi et al., 2003b; Bolognani et al., 1998; Kim and Sul, 2004; Meinguet and Gyselinck, 2009). In contrast, comparatively limited attention has been devoted to CFNI topology despite its reduced semiconductor requirements (Liu, 1993; Miraoui, 2025).

To clarify the trade-offs among these topologies, Table 1 summarizes the four representative configurations in terms of DC-bus structure, motor neutral accessibility, auxiliary semiconductor devices, semiconductor overrating cost factor (SOCF), post fault power ration factor (PPRF), attainable post-fault torque and fault-tolerant capability (Foster et al., 2010; Mirafzal, 2014; Tousizadeh et al., 2019; Welchko et al., 2004; Zhang et al., 2021, 2014).

Here, PPRF denotes the maximum achievable post-fault apparent power normalised by the rated apparent power under healthy conditions. SOCF represents the weighted apparent power rating of the complete set of semiconductor devices normalised with respect to that of the six insulated-gate bipolar transistors (IGBT) in a conventional healthy three-phase inverter. The calculation assumes that each semiconductor device withstands a DC-bus voltage of 1 pu and conducts a phase-current root mean square (RMS) of 1 pu. Under these assumptions, the conventional healthy inverter exhibits an SOCF of 1.

Table 1. Comparative analysis of SFI, CFI, SFNI, and CFNI topologies.

Topology Figure 1	Split bus DC	Accessible motor neutral	Auxiliary silicon components		SOCF	PPRF	Attainable torque (per unit)	Tolerate fault in	
			TRIAC	IGBT				Inverter side	Motor side
SFI (a)	Non	Non	3	2	1.83	1	1	√	×
CFI (b)	Oui	Non	3	0	1.5	0.5	1	√	×
SFNI (c)	Non	Oui	1	2	1.86	0.58	0.58	√	√
CFNI (d)	Oui	Oui	1	0	1.28	0.5	0.58	√	√

CFI, capacitor-based four-leg inverter; CFNI, capacitor-based four-leg neutral-point-connected inverter; PPRF, post-fault power ratio factor; SFI, switched-based four-leg inverter; SFNI, switched-based four-leg neutral-point-connected inverter; SOCF, semiconductor overrating cost factor.

The comparison highlights a fundamental compromise between post-fault capability and hardware complexity. The SFI preserves the rated torque but requires three triodes for alternating current (TRIAC) and two additional IGBTs, resulting in a relatively high SOCF of 1.83. The CFI eliminates the additional IGBTs and reduces the SOCF to 1.50, although its post-fault power capability is reduced. The SFNI can accommodate single-phase faults on either the inverter or motor side but requires additional semiconductor devices and exhibits the highest SOCF among the four topologies. In comparison, the CFNI requires only one auxiliary TRIAC and no additional IGBTs, yielding the lowest SOCF of 1.28 while retaining the capability to accommodate both inverter- and motor-side phase faults.

However, the CFNI presents some limitations. Its PPRF is reduced, especially under phase-loss (PL), and the post-fault torque and operation range are limited. In addition, the topology relies on a split DC bus and, therefore, requires sufficiently large DC-link capacitances to limit midpoint-voltage fluctuations. Despite these constraints, its low semiconductor count, structural simplicity, reduced SOCF and its capability to accommodate both inverter and motor-side phase faults make the CFNI particularly attractive for fault-tolerant traction applications where converter cost, volume and complexity are important considerations.

1.2. Research gap and motivation

Despite these attractive characteristics, fault-tolerant modulation and control of the CFNI topology have received considerably less attention than those of the CFI and SFNI configurations.

A recent work reported in Miraoui (2025) demonstrated the feasibility of fault-tolerant operation of a CFNI with PMSM under single-phase fault conditions using pulse width modulation (PWM)-based field-oriented control (FOC) methodology with adaptive reference adjustment. Building on these results, the present study further investigates the modulation stage by introducing a space vector pulse width modulation (SVPWM) strategy specifically adapted to the CFNI topology. SVPWM is selected because of its improved DC-link voltage utilisation and favourable harmonic performance, including reduced total harmonic distortion (THD), compared with conventional sinusoidal PWM (SPWM) (Kumar et al., 2010).

Under post-fault operation, each faulty phase leads to a specific voltage vector configuration and, consequently, to different sector definitions and switching sequences. Treating these three fault cases independently would require three distinct SVPWM algorithms.

These considerations motivate the development of a dedicated consolidated SVPWM framework for the CFNI topology, capable of handling the three phase-fault scenarios within a common formulation and thereby simplifying the modulation process. The proposed approach is conceptually inspired by the unified SVPWM strategy developed for the CFI topology in Zhidian and Lihao (2024a).

1.3. Main contributions

To address the aforementioned research gap, this paper proposes a consolidated SVPWM-based framework for CFNI-fed PMSM drive under single-phase fault conditions. The main contributions are:

1. A systematic analysis of the CFNI post-fault voltage-vector configurations is carried out for faults affecting phases a, b, and c, allowing the corresponding sectors and admissible vectors to be identified.
2. A consolidated SVPWM formulation is developed for the CFNI topology, enabling the three phase-fault scenarios to be handled using a common modulation algorithm.

3. The consolidated SVPWM procedure is expressed through four computational steps analogous to conventional SVPWM, facilitating its integration into standard drive-control architectures.
4. A remedial FOC strategy combining the CFNI topology and the proposed consolidated SVPWM is developed to maintain PMSM operation following a single-phase fault.
5. The proposed method is evaluated through detailed simulation with particular attention to phase-current and torque responses, speed tracking and the THD of current and torque under healthy and post-fault operating conditions.

1.4. Paper organisation

The paper is organised as follows: Section 2 details the SVPWM methodology for CFNI topology under single-phase faults. The voltage-vector configurations, sector definitions, and switching sequences are first established for each phase-fault scenario. A consolidated SVPWM formulation is then developed to handle the three fault cases within a common modulation framework. The proposed procedure is finally summarised through four computational steps analogous to those of conventional SVPWM. Section 3 introduces a remedial strategy based on FOC, integrating the consolidated SVPWM and the CFNI topology to ensure reliable operation of the PMSM under faulty conditions. Section 4 provides a comprehensive simulation evaluation, demonstrating the proposed method's effectiveness in maintaining system functionality. Key findings are discussed in detail, along with potential limitations. Section 5 concludes the paper with a summary of contributions and implications of the proposed methodology.

2. SVPWM for Faulty Case

The development of the proposed SVPWM strategy for CFNI topology is inspired by the principles of conventional SVPWM for healthy operating conditions in a three-phase inverter, which have been extensively reported in the literature (Bin Ibrahim et al., 2014; Kumar et al., 2010; Shu et al., 2007; YingYing et al., 2011).

2.1. Sector of the reference voltage vector

Starting with the case of a fault in phase a, after detecting a failure, the damaged phase is electrically isolated; then, using the TRIAC, the neutral point is connected to the midpoint DC-link capacitor as shown in Figure 1d.

The model describing the three-phase output voltage is presented as follows:

$$\begin{bmatrix} u_{an} \\ u_{bn} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} 0 \\ S_b u_{c1} + (S_b - 1)u_{c2} \\ S_c u_{c1} + (S_c - 1)u_{c2} \end{bmatrix} \quad (1)$$

S_a , S_b , and S_c represent the switching states of the three-leg transistors.

Considering the voltage oscillation at the capacitor midpoint and taking Δu as the voltage offset gives the expression of $u_{c1} = \frac{1}{2}V_{dc} + \Delta u$ and $u_{c2} = \frac{1}{2}V_{dc} - \Delta u$.

The transformed a-b-c to α - β coordinates using Clarke transformation A with $u_{an} = 0$ is expressed in Eq. (2).

$$\begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} = A \cdot \begin{bmatrix} 0 \\ u_{bn} \\ u_{cn} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ u_{bn} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} -\frac{1}{3}u_{bn} - \frac{1}{3}u_{cn} \\ \frac{1}{\sqrt{3}}u_{bn} - \frac{1}{\sqrt{3}}u_{cn} \end{bmatrix} \quad (2)$$

Considering Eqs (1) and (2), the inverter's model in α - β coordinates is expressed in Eq. (3).

$$\begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{3}V_{dc}(S_b + S_c - 1) - \frac{2}{3}\Delta u \\ \frac{1}{\sqrt{3}}V_{dc}(S_b - S_c) \end{bmatrix} \quad (3)$$

By combining the states of the four available inverter switches and, for simplicity in analysis and description, assuming $\Delta u = 0$, four voltage space vectors are obtained and their components are summarised in Table 2.

For the cases of faults in b or c, and by following the same analysis used in a, we obtain four voltage space vectors as reported in Tables 3 and 4.

Based on the three summarised tables, the distribution of the basic voltage vectors in the α - β coordinate system is illustrated in Figure 2.

Table 2. Available voltage vectors with neutral point connected to the midpoint of the DC-link capacitor and phase a eliminated.

S_b	S_c	u_α	u_β	V_x	Amplitude
0	0	$V_{dc}/3$	0	V_1	$V_{dc}/3$
0	1	0	$-V_{dc}/\sqrt{3}$	V_4	$V_{dc}/\sqrt{3}$
1	0	0	$V_{dc}/\sqrt{3}$	V_2	$V_{dc}/\sqrt{3}$
1	1	$-V_{dc}/3$	0	V_3	$V_{dc}/3$

Table 3. Available voltage vectors with neutral point connected to the midpoint of the DC-link capacitor and phase b eliminated.

S_c	S_a	u_α	u_β	V_x	Amplitude
0	0	$-V_{dc}/6$	$\sqrt{3}V_{dc}/6$	V_1	$V_{dc}/3$
0	1	$V_{dc}/2$	$\sqrt{3}V_{dc}/6$	V_4	$V_{dc}/\sqrt{3}$
1	0	$-V_{dc}/2$	$-\sqrt{3}V_{dc}/6$	V_2	$V_{dc}/\sqrt{3}$
1	1	$V_{dc}/6$	$-\sqrt{3}V_{dc}/6$	V_3	$V_{dc}/3$

Table 4. Available voltage vectors with neutral point connected to the midpoint of the DC-link capacitor and phase c eliminated.

S_a	S_b	u_α	u_β	V_x	Amplitude
0	0	$-V_{dc}/6$	$-\sqrt{3}V_{dc}/6$	V_1	$V_{dc}/3$
0	1	$-V_{dc}/2$	$\sqrt{3}V_{dc}/6$	V_4	$V_{dc}/\sqrt{3}$
1	0	$V_{dc}/2$	$-\sqrt{3}V_{dc}/6$	V_2	$V_{dc}/\sqrt{3}$
1	1	$V_{dc}/6$	$\sqrt{3}V_{dc}/6$	V_3	$V_{dc}/3$

2.2. Unification of the three cases

To address the complexity of implementing three separate SVPWM algorithms for each phase fault, a unified SVPWM approach is proposed in this section.

By comparing the three basic voltage vector distributions in Figure 2, it can be observed that they contain the same number of vectors with identical amplitudes, while differing only in the angular positions of the vectors in the $\alpha\beta$ plane. Therefore, the three distributions can be expressed in a common $\alpha'\beta'$ representation through an appropriate coordinate rotation. For the distribution in Figure 2a, no rotation is required and the $\alpha'\beta'$ axes coincide

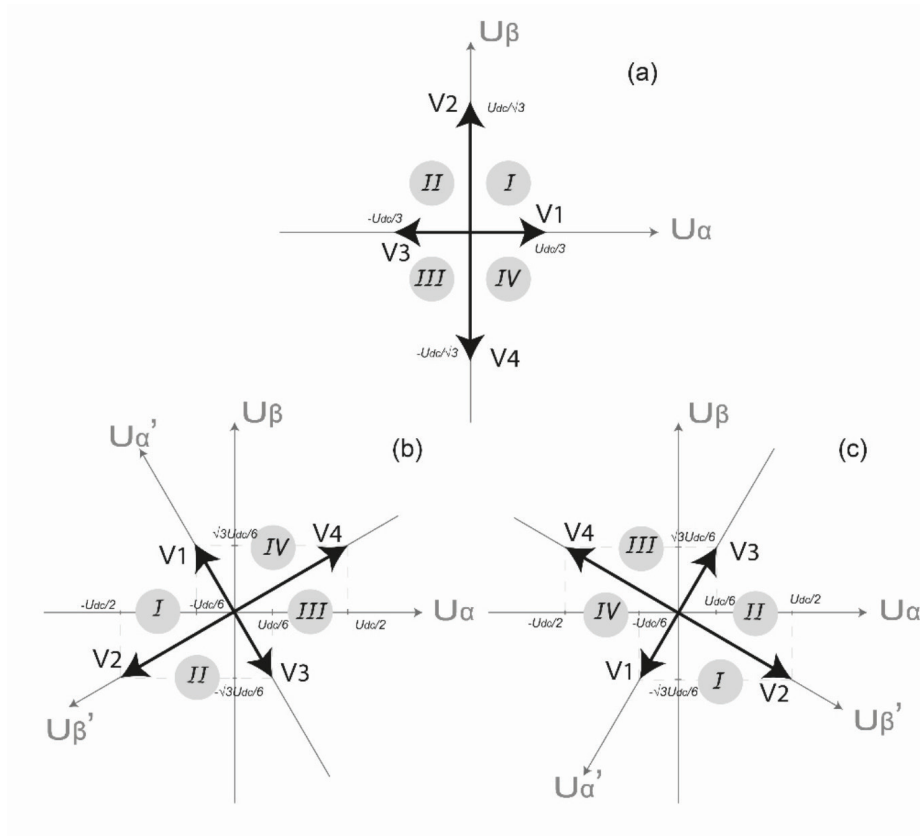


Figure 2. Voltage vectors in the $\alpha\beta$ plane. (a) Fault in a, (b) fault in b, and (c) fault in c.

with the original $\alpha\beta$ axes. For Figure 2b, the $\alpha'\beta'$ axes are rotated by $\frac{2\pi}{3}$ with respect to the $\alpha\beta$ axes, leading to the coordinate transformation given in Eq. (4). Similarly, for Figure 2c, the $\alpha'\beta'$ axes are rotated by $\frac{-2\pi}{3}$ with respect to the original $\alpha\beta$ axes, resulting in the transformation given in Eq. (5).

After these transformations, the three cases exhibit the same basic voltage vector distribution in the $\alpha'\beta'$ plane, thereby enabling the development of a unified SVPWM approach.

$$\begin{bmatrix} u_{\alpha'} \\ u_{\beta'} \end{bmatrix} = \begin{bmatrix} \cos \frac{2\pi}{3} & \sin \frac{2\pi}{3} \\ -\sin \frac{2\pi}{3} & \cos \frac{2\pi}{3} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} u_{\alpha'} \\ u_{\beta'} \end{bmatrix} = \begin{bmatrix} \cos \frac{-2\pi}{3} & \sin \frac{-2\pi}{3} \\ -\sin \frac{-2\pi}{3} & \cos \frac{-2\pi}{3} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} \quad (5)$$

In the sections that follow, we will present the additional steps required to complete the SVPWM process based on the common voltage vectors depicted in Figure 3.

2.3. Sector identification

The sector selection is determined according to the flowchart illustrated in Figure 4, based on the common voltage vectors in the $\alpha'\beta'$ plane shown in Figure 3.

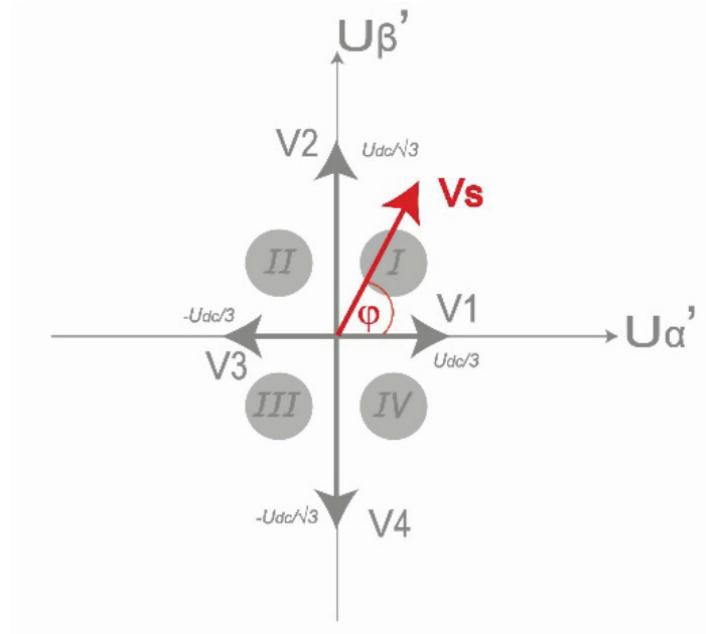


Figure 3. Common voltage vectors in $\alpha'\beta'$ plane.

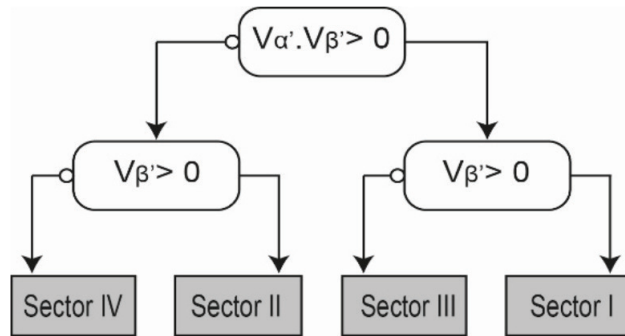


Figure 4. Flowchart of sector identification.

2.4. Time calculation

The common space vector, as depicted in Figure 3, has only four distinct space vectors available. However, additional space vectors can be obtained by alternately applying active and zero vectors over the modulator's switching period T_s . For instance, the active vectors V_1 and V_2 can be combined to synthesise a reference space vector V_s with an angle between 0° and 90° .

Then the average space vector's amplitude can be expressed as:

$$\bar{V}_s = \frac{\bar{V}_1 T_1 + \bar{V}_2 T_2}{T_s} \quad (6)$$

with $V_s = \sqrt{V_{\alpha'}^2 + V_{\beta'}^2}$, $\varphi = \arctan\left(\frac{V_{\beta'}}{V_{\alpha'}}\right)$, and $T_s = T_k + T_{k+1} + T_0$.

For any sector k (I, II, III, and VI), we can synthesise the reference space vector $\vec{V}_s$ using the following equation:

$$\vec{V}_s = \frac{\vec{V}_k T_k + \vec{V}_{k+1} T_{k+1}}{T_s} \quad (7)$$

Now, based on Figure 3 and the analysis discussed earlier, we can derive the time calculations in Eq. (8)

$$\begin{cases} T_k = \frac{V_s}{V_k} T_s \cos \theta \\ T_{k+1} = \frac{V_s}{V_{k+1}} T_s \sin \theta \end{cases} \quad (8)$$

with $\theta = \varphi - (k-1)\frac{\pi}{2}$.

It is essential to consider that the values of V_k and V_{k+1} vary across the sectors; therefore, the values of T_k and T_{k+1} for each sector are given in Table 5.

Table 5. Adjusted time calculations.

Sector I	Sector II	Sector III	Sector VI
$T_1 = 3 \frac{V_s}{V_{dc}} T_s \cos \theta$	$T_1 = \sqrt{3} \frac{V_s}{V_{dc}} T_s \cos \theta$	$T_1 = 3 \frac{V_s}{V_{dc}} T_s \cos \theta$	$T_1 = \sqrt{3} \frac{V_s}{V_{dc}} T_s \cos \theta$
$T_2 = \sqrt{3} \frac{V_s}{V_{dc}} T_s \sin \theta$	$T_2 = 3 \frac{V_s}{V_{dc}} T_s \sin \theta$	$T_2 = \sqrt{3} \frac{V_s}{V_{dc}} T_s \sin \theta$	$T_2 = 3 \frac{V_s}{V_{dc}} T_s \sin \theta$

2.5. Switching sequence generation

To reduce switching losses, it is necessary to optimise the switching sequence. Figure 5 illustrates the possible switching sequences. As can be observed, the active vectors are selected by considering the switching states of the power switches in Table 2. Consequently, only one switch changes its state during each transition, thereby minimising switching losses.

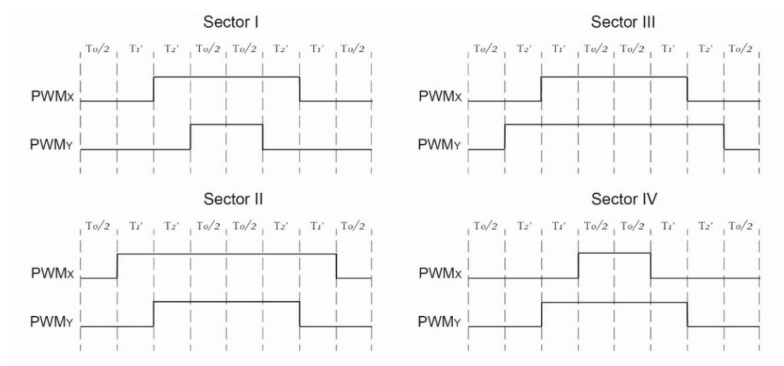


Figure 5. Optimal switching patterns for the four sectors. PWM, pulse width modulation.

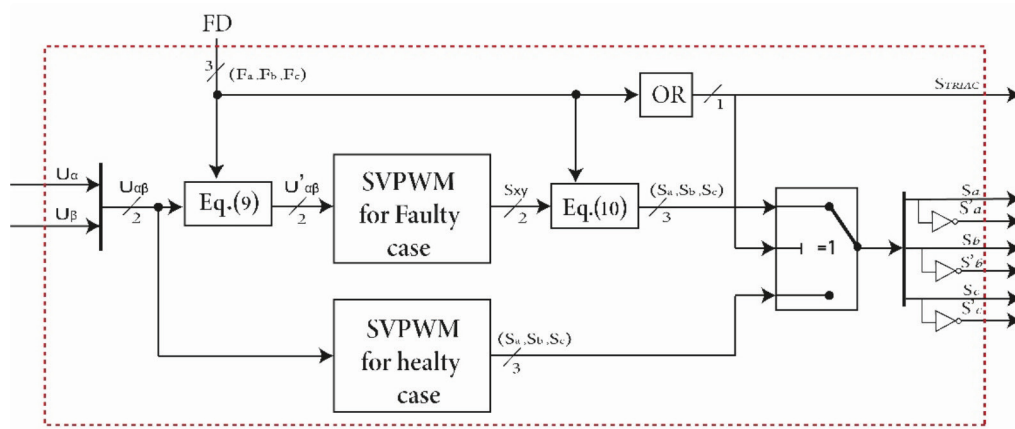
The notation (PWMx, PWMy) was adopted to provide a generalised formulation independent of the faulty phase. Specifically, under a phase-a fault, it corresponds to (PWMb, PWMc), under a phase-b fault, to (PWMc, PWMa), and under a phase-c fault, to (PWMa, PWMb). This notation was derived from the analysis of Tables 2–4, which led to the formulation of Table 6.

Table 6. Summarised switching states for the three faulty cases.

	Fault in a		Fault in b		Fault in c	
	S_x	S_y	S_x	S_y	S_x	S_y
	S_b	S_c	S_c	S_a	S_a	S_b
V_1	0	0	0	0	0	0
V_2	1	1	1	0	0	0
V_3	1	1	1	1	1	1
V_4	0	0	0	1	1	1

3. Control System Block Diagram

FOC is a widely used technique for managing a standard three-phase PMSM by separating the control of magnetic flux and torque via the d - and q -current axes (Chikh et al., 2011; Miraoui et al., 2025; Nicola et al., 2022). In this remedial strategy, as shown in Figure 7, the same FOC method is employed to produce the components V_d and V_q which are then transformed from the d - q to α - β coordinate system before being input into the consolidated SVPWM in Figure 6.

**Figure 6.** Proposed consolidated SVPWM control block diagram. SVPWM, space vector pulse width modulation.

As inputs U_α and U_β are processed through the system, the conventional SVPWM directly generates the six switching signals under healthy operation. However, if a fault occurs and is detected, the fault detection signal, which is represented in Figure 6 by a three-bit signal fault detection (FD) (F_a, F_b, F_c), activates the SVPWM algorithm for the faulty operation. Each bit identifies the corresponding faulty phase, where F_a, F_b , and F_c are associated with phases a, b, and c, respectively. Under a fault in phase a, only the bit F_a is set to 1.

In the faulty case, the processing is carried out using U_α' and U_β' as inputs, obtained from Eq. (9). Eq. (9) combines the coordinate transformations introduced in Eqs (4) and (5) with the FD signal to automatically select the appropriate transformation according to the faulty phase. For example, when $F_b = 1$, Eq. (9) reduces to Eq. (4). Thus, regardless of the faulty phase, the voltage vectors are expressed in the common $\alpha\beta'$ reference frame shown in Figure 3.

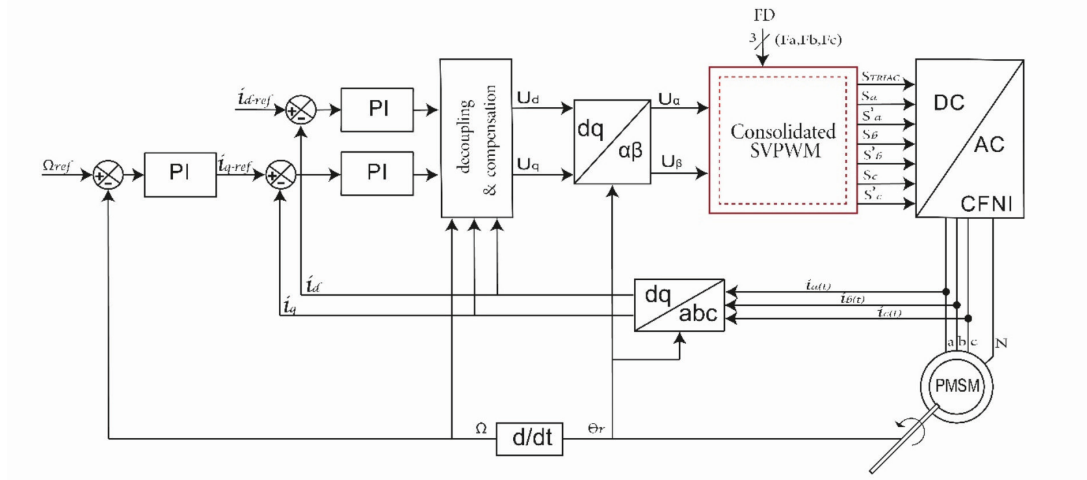


Figure 7. Proposed single-phase FTC block diagram. CFNI, capacitor-based four-leg neutral-point-connected inverter; FTC, fault-tolerant control; PMSM, permanent magnet synchronous motor; SVPWM, space vector pulse width modulation; PI, proportional-integral.

The unified SVPWM generates the two switching signals S_x and S_y , which must be assigned to the two healthy phases according to the detected faulty phase. To map these output signals to the corresponding healthy phases, Eq. (10) is employed. This equation is derived from the relationships summarised in Table 6. For example, for a phase-b fault, $F_b = 1$, Eq. (10) gives $S_c = S_x$ and $S_a = S_y$.

$$\begin{bmatrix} u_\alpha' \\ u_\beta' \end{bmatrix} = \begin{bmatrix} F_a - \frac{1}{2}(F_b + F_c) & \frac{\sqrt{3}}{2}(F_b - F_c) \\ -\frac{\sqrt{3}}{2}(F_b - F_c) & F_a - \frac{1}{2}(F_b + F_c) \end{bmatrix} \cdot \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \begin{bmatrix} F_c & F_b \\ F_a & F_c \\ F_b & F_a \end{bmatrix} \cdot \begin{bmatrix} S_x \\ S_y \end{bmatrix} \quad (10)$$

4. Simulation and Results

The proposed remedial strategy illustrated in Figure 7, together with the power configuration, was evaluated through a co-simulation approach using power simulation (PSIM) and MATLAB/Simulink (The MathWorks, MATLAB R2018b, United States). The control scheme was developed in MATLAB/Simulink, and the power structure was implemented in PSIM. The nominal ratings and parameters of the PMSM and CFNI used in the simulations are provided in Table 7.

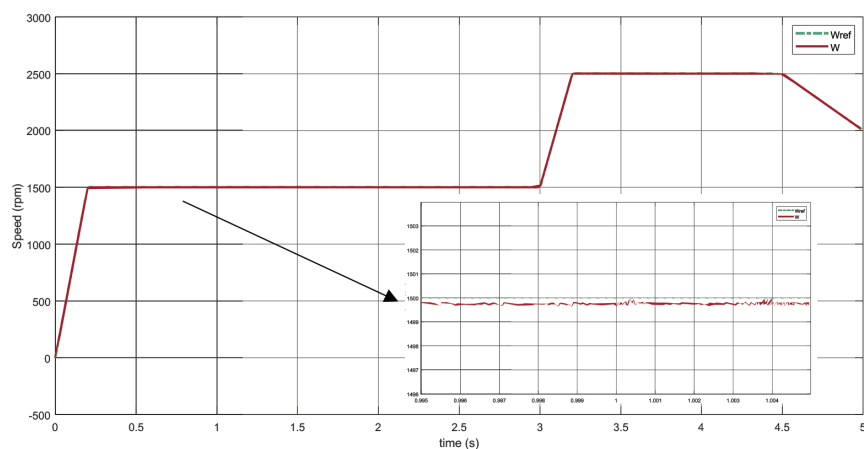
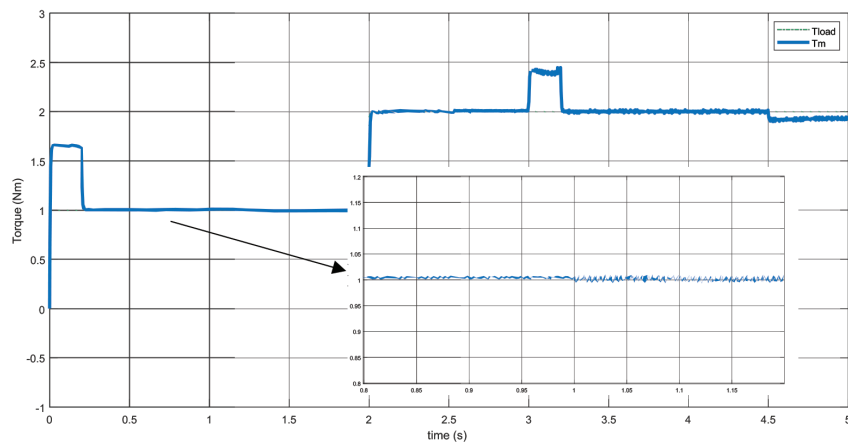
Three separate single-phase fault scenarios were considered by introducing a fault in phases a, b, and c. In each case, the fault was applied at $t = 1$ s. Following fault occurrence, the faulty leg was isolated, and the TRIAC shown in Figure 1d was triggered to connect the motor neutral point to the midpoint of the DC-link capacitors. Simultaneously, the consolidated SVPWM switches from the conventional SVPWM to the proposed post-fault modulation strategy.

The PMSM initially operated at a speed reference of 1,500 rpm and a torque reference of 1 Nm. At $t = 2$ s, the torque reference was increased from 1 Nm to 2 Nm. Additional speed reference variations were then applied under post-fault operation to evaluate the performance of the proposed strategy at different operating points. The following analysis separately evaluates the speed, torque, and current performances using quantitative indices in addition to the time-domain responses.

Figure 8 presents the rotor-speed response before and after fault occurrence. Under healthy operation, the measured speed follows the reference at 1499.8 rpm, corresponding to a relative error of 0.013%.

Table 7. System parameters.

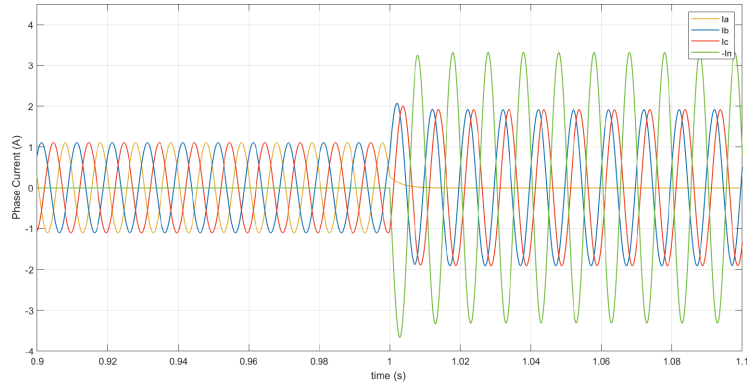
Parameters	Values
DC-voltage	220V
Cbus	4.4 mF
PWM frequency	16 kHz
Rated power	1,100 W
Rated speed	3,000 rpm
Resistance and inductance	2.875 Ω and 8.5 mH
Pole pairs	4
Viscous friction	0.001 Nms
Rotational inertia J	0.0008 kg·m ²
Permanent magnet flux	0.175 Wb

**Figure 8.** Speed response before and after a fault occurs in phase a at 1 s.**Figure 9.** Torque response before and after a fault occurs in phase a at 1 s.

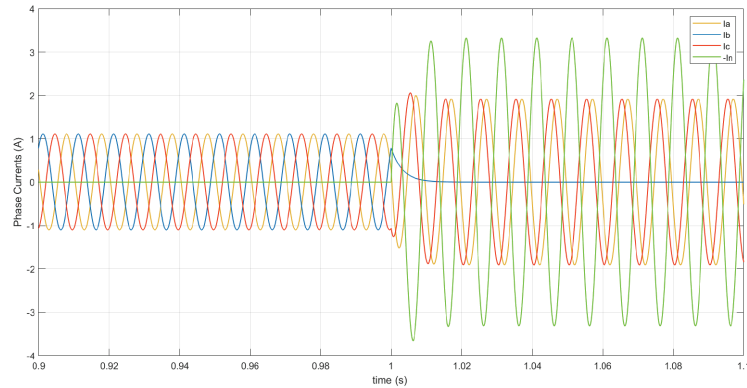
The enlarged view at 1 s shows that the transition from healthy to post-fault operation introduces a very small perturbation, and the speed remains tightly regulated around its reference immediately after reconfiguration.

Furthermore, as shown in Figure 8, the PMSM continues to follow the changes of the speed reference from 1,500 rpm to 2,500 rpm and later to 2,000 rpm, demonstrating that the proposed approach preserves the speed tracking capability after fault accommodation.

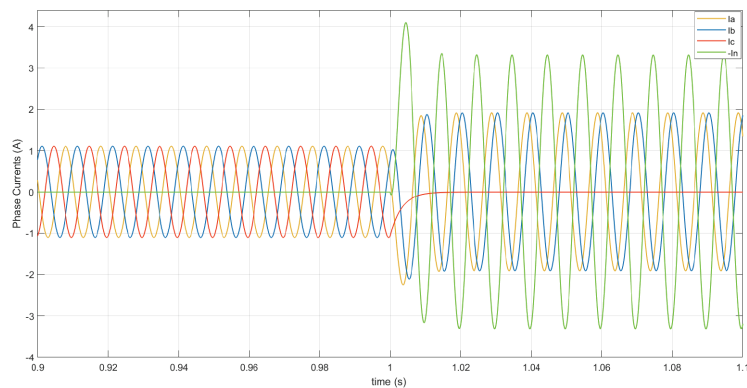
Figure 9 presents the rotor torque response under healthy and faulty conditions. The torque follows the 1 Nm reference with a mean value of 1.003 Nm under healthy operation and 0.9999 Nm after fault reconfiguration, confirming the capability of the proposed strategy to preserve the average torque production.



(a)



(b)



(c)

Figure 10. Current response before and after a fault occurs at 1 s, (a) in phase a, (b) in phase b, and (c) in phase c.

The main post-fault effect is, therefore, an increase in torque oscillations: the torque ripple increases from approximately 0.56% to 1.61%, while the torque distortion rises from 0.14% to 0.33%. Nevertheless, the torque reference remains accurately tracked after the load increase to 2 Nm at $t = 2$ s.

Figure 10 presents the phase and neutral currents for faults occurring in phases a, b, and c. Before the fault, the three-phase currents are balanced. After reconfiguration, the current of the faulty phase is suppressed while the two healthy phase currents are increased and the neutral current becomes the sum of the two healthy phase currents.

Table 8 summarises the current amplitudes and phase displacements before and after fault occurrence in the three fault scenarios.

In line with observations in the literature (Bianchi et al., 2003b; Bolognani et al., 1998; Kim and Sul, 2004; Liu, 1993; Meinguet and Gyselinck, 2009), the phase-current displacement is reduced to one-sixth of a period, while the amplitude of the current increases from 1.105 A to 1.909 A, corresponding to approximately 1.73 times the healthy value. Additionally, the amplitude of the neutral current reaches 3.315 A, three times higher than the phase currents under normal operation. This increase results from the need to maintain electromagnetic torque after the loss of one phase, requiring the two remaining healthy phases to carry higher currents.

The harmonic quality of the currents was evaluated through FFT analysis, as shown in Figure 11. The results show that the current THD remains below 1%, with a value of 0.28% for a speed of 1,500 rpm.

The combined speed, torque and current results confirm the effectiveness of the proposed remedial strategy. In terms of practical limitations, maintaining the increased post-fault current levels for extended durations may require oversizing of the inverter switches and leads to increased copper losses in the motor. Alternatively, the allowable peak currents of both the inverter and the motor, together with their permissible overload durations, must be considered. As these limits are approached, a smooth transition towards a degraded operating mode should be applied to avoid an abrupt torque loss, while protecting the drive from excessive electrical and thermal stress.

From an implementation perspective, this unified approach reduces the number of required SVPWM algorithms from four to two. Without consolidation, the complete controller would require one conventional SVPWM for healthy operation and three dedicated SVPWM algorithms corresponding to the three possible faulty phases. This

Table 8. Current amplitudes and phase displacements in the three faulty scenarios.

	Healthy case		Fault in a		Fault in b		Fault in c	
	Amp.	Deph.	Amp.	Deph.	Amp.	Deph.	Amp.	Deph.
i_a	i_N	0	0	-	$\sqrt{3} i_N$	$-\pi/6$	$\sqrt{3} i_N$	$\pi/6$
i_b	i_N	$2\pi/3$	$\sqrt{3} i_N$	$\pi/6$	0	-	$\sqrt{3} i_N$	$-\pi/6$
i_c	i_N	$-2\pi/3$	$\sqrt{3} i_N$	$-\pi/6$	$\sqrt{3} i_N$	$\pi/6$	0	-
i_n	0	-	$3i_N$	0	$3i_N$	0	$3i_N$	0

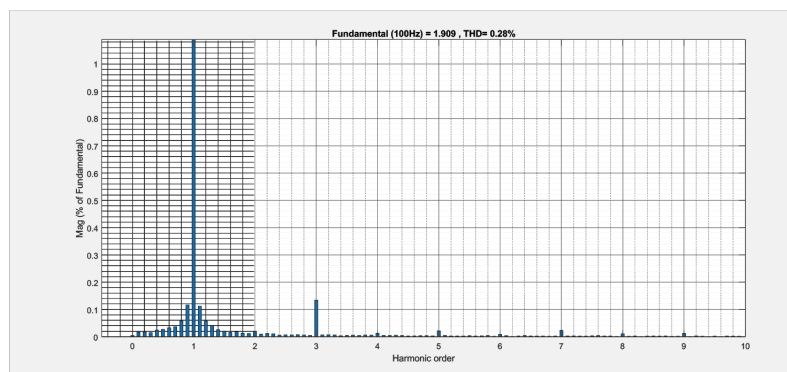


Figure 11. Current THD in faulty case. THD, total harmonic distortion.

consolidation reduces the number of algorithms and simplifies the control architecture. Since the present study is simulation-based, no specific digital processor is considered; therefore, execution time and memory savings are not quantitatively reported.

5. Conclusion

This paper presented a single-phase FTC strategy applicable to traction drive systems, employing a consolidated SVPWM technique dedicated to a CFNI. The proposed approach unifies the modulation process for faults occurring in phases a, b, and c, thereby avoiding the use of three separate fault-dependent SVPWM algorithms and simplifying the control implementation.

This method was demonstrated through simulations on a PMSM considering faults independently occurring in phases a, b, and c. Simulation results confirmed that, after fault detection and converter reconfiguration to eliminate the faulty phase, the torque production and speed tracking are maintained continuously. The two healthy phase currents increase to approximately 1.73 times their healthy state value, with the required phase displacement, while the neutral current ensures the return path. The proposed approach also preserves good waveform quality under post-fault operation; current THD remains below 1% in the investigated operating conditions. The results obtained under load and speed variation further demonstrate the ability to maintain stable operation.

Nonetheless, maintaining the increased post-fault currents for extended periods may require oversized inverter switches and lead to higher motor copper losses. Otherwise, overload capability and permissible duration must be considered. Once these limits are attained, a smooth transition towards a degraded operation mode should be applied to avoid abrupt torque loss and excessive electrical and thermal stress.

Overall, the proposed consolidated SVPWM provides an effective solution for fault-tolerant operation of CFNI-based PMSM traction drive systems. Future work could focus on experimental validation across different motor types and, therefore, extend the approach to other high-dependability applications.

References

- Adamczyk, M. and Orłowska-Kowalska, T. (2023). Active Current Sensor Fault-Tolerant Control of Induction Motor Drive With Online Neural Network-Based Rotor and Stator Resistance Estimation. *Power Electronics and Drives*, 8(1), pp. 235–251. doi: 10.2478/pead-2023-0016
- Ahmed Baba, M., Naoui, M. and Cherkaoui, M. (2023). Fault-Tolerant Control Strategy for Hall Sensors in BLDC Motor Drive for Electric Vehicle Applications. *Sustainability*, 15(13), p. 10430. doi: 10.3390/su151310430
- Altin, N., Ozdemir, S., Komurcugil, H., Sefa, I., & Biricik, S. (2018). Sliding-mode and proportional-resonant based control strategy for three-phase two-leg T - type grid-connected inverters with LCL filter. In: *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Washington, DC, USA, pp. 4492–4497. doi: 10.1109/IECON.2018.8591542
- Bhuiyan, E. A., Akhand, Md. M. A., Das, S. K., Ali, Md. F., Tasneem, Z., Islam, Md. R., Saha, D. K., Badal, F. R., Ahamed, Md. H and Moyeen, S. I. (2020). A Survey on Fault Diagnosis and Fault Tolerant Methodologies for Permanent Magnet Synchronous Machines. *International Journal of Automation and Computing*, 17(6), pp. 763–787. doi: 10.1007/s11633-020-1250-3
- Bianchi, N., Bolognani, S., Zigliotto, M. and Zordan, M. (2003a). Innovative Remedial Strategies for Inverter Faults in IPM Synchronous Motor. *IEEE Transactions on Energy Conversion*, 18(2), pp. 306–314. doi: 10.1109/TEC.2002.808334
- Bianchi, N., Bolognani, S., Zigliotto, M. and Zordan, M. (2003b). Innovative Remedial Strategies for Inverter Faults in IPM Synchronous Motor Drives. *IEEE Transactions on Energy Conversion*, 18(2), pp. 306–314. doi: 10.1109/TEC.2002.808334
- Bin Ibrahim, Z., Hossain, Md. L., Bin Bugis, I., Nik Mahadi, N. M. and Abu Hasim, A. S. (2014). Simulation Investigation of SPWM, THIPWM and SVPWM Techniques for Three Phase Voltage Source Inverter. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 4(2), pp. 223–240. doi: 10.11591/ijpeds.v4i2.5833
- Bolognani, S., Zigliotto, M., & Zordan, M. (1998). Experimental fault-tolerant control of a PMSM drive. In: *IECON '98. Proceedings of the 24th Annual*

- Conference of the IEEE Industrial Electronics Society (Cat. No.98CH36200)*, 1, Aachen, pp. 492–497. doi: 10.1109/IECON.1998.724292
- Chikh, K., Saad, A., Khafallah, M., & Yousfi, D. (2011). PMSM vector control performance improvement by using pulse with modulation and anti-windup PI controller. In: *2011 International Conference on Multimedia Computing and Systems*, pp. 1–7. doi: 10.1109/ICMCS.2011.5945633
- DeAraujo Ribeiro, R. L., Jacobina, C. B., Da Silva, E. R. C. and Lima, A. M. N. (2004). Fault-Tolerant Voltage-Fed PWM Inverter AC Motor Drive Systems. *IEEE Transactions on Industrial Electronics*, 51(2), pp. 439–446. doi: 10.1109/TIE.2004.825284
- Elsayed, M. E., Hamad, M. S., & Ashour, H. A. (2022). Open-phase fault-tolerant control approach for EV PMSM based on four-leg VSI. In: *2022 23rd International Middle East Power Systems Conference (MEPCON)*, Cairo, pp. 1–7. doi: 10.1109/MEPCON55441.2022.10021774
- Estima, J. O., & Cardoso, A. J. M. (2012). Fast fault detection, isolation and reconfiguration in fault-tolerant permanent magnet synchronous motor drives. In: *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, pp. 3617–3624. doi: 10.1109/ECCE.2012.6342310
- Fadil, H., Elhafyani, M. L. and Zouggar, S. (2018). Enhanced Three-Phase Inverter Faults Detection and Diagnosis Approach—Design and Experimental Evaluation. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 9(2), p. 559. doi: 10.11591/ijpeds.v9.i2.pp559-570
- Foster, M. P., Hoang, K. D., Stone, D. A., & Zhu, Z. Q. (2010). Comparative study of current vector control performance of alternate fault tolerant inverter topologies for three-phase pm brushless ac machine with one phase open circuit fault. In: *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, Brighton, pp. 413–413. doi: 10.1049/cp.2010.0052
- Gherghina, I.-S., Bizon, N., Iana, G.-V. and Vasilică, B.-V. (2025). Recent Advances in Fault Detection and Analysis of Synchronous Motors: A Review. *Machines*, 13(9), p. 815. doi: 10.3390/machines13090815
- Hang, J., Zhang, J., Qin, H., Ding, S., Huang, Y. and Hua, W. (2023). A Simplified Model Predictive Voltage Control for Three-Phase Four-Switch Inverter-Fed PMSM Drives With Capacitor Voltage Offset Suppression and Current Ripple Reduction. *IEEE Transactions on Power Electronics*, 38(4), pp. 5154–5166. doi: 10.1109/TPEL.2022.3225831
- Hicham, F., Yousfi, D., Mohamed Larbi, E. and Youness, A. (2017). Four-Switch Three-Phase PMSM Converter with Output Voltage Balance and DC-Link Voltage Offset Suppression. *Information*, 8(1), p. 11. doi: 10.3390/info8010011
- Hu, K., Liu, Z., Tasiu, I. A. and Chen, T. (2021). Fault Diagnosis and Tolerance With Low Torque Ripple for Open-Switch Fault of IM Drives. *IEEE Transactions on Transportation Electrification*, 7(1), pp. 133–146. doi: 10.1109/TTE.2020.3006057
- Huang, S., Guo, X., Wang, R. and Mei, Y. (2021). A SVPWM Algorithm Based on Four-Switch Three-Phase Inverter for PMSM Under the Imbalance of Bus Capacitor Voltage. *Journal of Power Electronics*, 21(12), pp. 1812–1822. doi: 10.1007/s43236-021-00324-7
- Khaneghah, M. Z., Alzayed, M. and Chaoui, H. (2023). Fault Detection and Diagnosis of the Electric Motor Drive and Battery System of Electric Vehicles. *Machines*, 11(7), p. 713. doi: 10.3390/machines11070713
- Kim, J.-H. and Sul, S.-K. (2004). A Carrier-Based PWM Method for Three-Phase Four-Leg Voltage Source Converters. *IEEE Transactions on Power Electronics*, 19(1), pp. 66–75. doi: 10.1109/TPEL.2003.820559
- Kommuri, S. K., Defoort, M., Karimi, H. R. and Veluvolu, K. C. (2016). A Robust Observer-Based Sensor Fault-Tolerant Control for PMSM in Electric Vehicles. *IEEE Transactions on Industrial Electronics*, 63(12), pp. 7671–7681. doi: 10.1109/TIE.2016.2590993
- Kumar, K. V., Michael, P. A., John, J. P. and Kumar, D. S. S. (2010). Simulation and Comparison of SPWM and SVPWM Control for Three Phase Inverter. *APRN Journal of Engineering and Applied Sciences*, 5(7), pp. 61–74.
- Kumar, M. P., Velpula, S., Saiprakash, C. and Sahoo, B. (2025). Advancements in Fault Detection and Diagnosis Methods for Electric Vehicles: A Review. *Discover Applied Sciences*, 7(11), p. 1235. doi: 10.1007/s42452-025-07758-9
- Liu, T.-H. (1993). A Strategy for Improving Reliability of Field-Oriented Controlled Induction Motor Drives. *IEEE Transactions on Industry Applications*, 29(5), pp. 910–918. doi: 10.1109/28.245714
- Li, H., Zhu, Z.-Q., Azar, Z., Clark, R. and Wu, Z. (2025). Fault Detection of Permanent Magnet Synchronous Machines: An Overview. *Energies*, 18(3), p. 534. doi: 10.3390/en18030534
- Li, W., Xuan, S., Gao, Q. and Luo, L. (2019). Investigation of a Four-Switch Four-Leg Inverter: Modulation, Control, and Application to an IPMSM Drive. *IEEE Transactions on Power Electronics*, 34(6), pp. 5655–5666. doi: 10.1109/TPEL.2018.2869491

- Meinguet, F., & Gyselinck, J. (2009). Control strategies and reconfiguration of four-leg inverter PMSM drives in case of single-phase open-circuit faults. In: *2009 IEEE International Electric Machines and Drives Conference*, Miami, pp. 299–304. doi: 10.1109/IEMDC.2009.5075221
- Mirafzal, B. (2014). Survey of Fault-Tolerance Techniques for Three-Phase Voltage Source Inverters. *IEEE Transactions on Industrial Electronics*, 61, pp. 5192–5202. doi: 10.1109/TIE.2014.2301712
- Miraoui, M., Elhafyani, M. L. and Zerdani, S. (2025). Performance evaluation of three controllers for PMSM: FOC with PI, FOC with Fuzzy-PI, backstepping. In: B. Hajji, A. Gagliano, A. Mellit, A. Rabhi, M. Cali, eds., *Proceedings of the 4th International Conference on Electronic Engineering and Renewable Energy Systems*—vol. 1, Springer Nature, pp. 207–216. doi: 10.1007/978-981-96-0644-3_19
- Miraoui, M., Elhafyani, M. L. and Zekraoui, H. (2026). Single-phase fault-tolerant control for PMSM with capacitor-based four-leg neutral-point-connected inverter. In: S. Motahhir, B. Bossoufi, J.M. Guerrero, eds., *Digital Technologies and Applications. ICDTA 2025. Lecture Notes in Networks and Systems*, vol. 1640. Cham: Springer, pp. 399–406. https://doi.org/10.1007/978-3-032-07785-1_35
- Nicola, M., Nicola, C.-I., Selişteanu, D. and Ionete, C. (2022). Control of PMSM Based on Switched Systems and Field-Oriented Control Strategy. *Automation*, 3(4), pp. 646–673. doi: 10.3390/automation3040033
- Orlowska-Kowalska, T., Wolkiewicz, M., Pietrzak, P., Skowron, M., Ewert, P., Tarchala, G., Krzysztofki, M. and Kowalski, C. T. (2022). Fault Diagnosis and Fault-Tolerant Control of PMSM Drives—State of the Art and Future Challenges. *IEEE Access*, 10, pp. 59979–60024. doi: 10.1109/ACCESS.2022.3180153
- Romdhane, M., Naoui, M., Gacem, A. and Mansouri, A. (2026a). Hybrid Type-2 Fuzzy Logic–Extended Kalman Filter Approach for ITSC Fault Detection in PMSM Drives for Electric Vehicles. *Power Electronics and Drives*, 11(1), pp. 61–78. doi: 10.2478/pead-2026-0004
- Romdhane, M., Naoui, M. and Mansouri, A. (2026b). Impact of electrical faults on PMSM performance in electric vehicles: HMI monitoring and modeling-FOC-based evaluation under standard driving cycles. *Bridging Human-Machine Interaction for Energy Infrastructure*. Hershey: IGI Global Scientific Publishing, pp. 1–36. <https://www.igi-global.com/chapter/impact-of-electrical-faults-on-pmsm-performance-in-electric-vehicles/400046>
- Shu, Z., Tang, J., Guo, Y. and Lian, J. (2007). An Efficient SVPWM Algorithm With Low Computational Overhead for Three-Phase Inverters. *IEEE Transactions on Power Electronics*, 22(5), pp. 1797–1805. doi: 10.1109/TPEL.2007.904228
- Teler, K. (2026). Analysis of Open-Loop Current Estimators for Current Sensor Fault Compensation in PMSM Motor Drive. *Power Electronics and Drives*, 11(1), pp. 23–40. doi: 10.2478/pead-2026-0002
- Tousizadeh, M., Che, H. S., Selvaraj, J., Rahim, N. A. and Ooi, B.-T. (2019). Performance Comparison of Fault-Tolerant Three-Phase Induction Motor Drives Considering Current and Voltage Limits. *IEEE Transactions on Industrial Electronics*, 66(4), pp. 2639–2648. doi: 10.1109/TIE.2018.2850006
- Welchko, B. A., Lipo, T. A., Jahns, T. M. and Schulz, S. E. (2004). Fault Tolerant Three-Phase AC Motor Drive Topologies: A Comparison of Features, Cost, and Limitations. *IEEE Transactions on Power Electronics*, 19(4), pp. 1108–1116. doi: 10.1109/TPEL.2004.830074
- YingYing, J., XuDong, W., LiangLiang, M., ShuCai, Y., & HaiXing, Z. (2011). Application and Simulation of SVPWM in three phase inverter. In: *Proceedings of 2011 6th International Forum on Strategic Technology*, 1, Harbin, pp. 541–544. doi: 10.1109/IFOST.2011.6021082
- Yousfi, D., Halelfadl, A., & Kard, M. E. (2009). Sensorless Control of Permanent Magnet Synchronous Motor. In: *2009 International Conference on Multimedia Computing and Systems*, Ouarzazate, pp. 341–344. doi: 10.1109/MMCS.2009.5256677.
- Zerdani, S., El Hafyani, M. L., Fadil, H., & Zouggar, I. (2019). Active fault tolerant control for Permanent Magnet Synchronous Motor drives. In: *2019 International Conference of Computer Science and Renewable Energies (ICCSRE)*, Agadir, pp. 1–7. doi: 10.1109/ICCSRE.2019.8807463
- Zerdani, S., El Hafyani, M. L., Fadil, H. and Zouggar, S. (2021). Newly Fault-Tolerant Indirect Vector Control for Traction Inverter. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 12(3), p. 1576. doi: 10.11591/ijpeds.v12.i3.pp1576-1585
- Zerdani, S., El Hafyani, M. L. and Zouggar, S. (2022). Application of Power Spectral Density and the Support Vector Machine to Fault Diagnosis for Permanent Magnet Synchronous Motor. *SN Applied Sciences*, 4(9), p. 245. doi: 10.1007/s42452-022-05115-8
- Zhang, X., Gauthier, J.-Y. and Lin-Shi, X. (2021). Cost-Efficient Fault-Tolerant Scheme for Three-Phase

- SPMSMs Fed by Multi-Functional Converter System Under Open-Phase Faults. *IEEE Transactions on Industrial Electronics*, 69, pp. 1–1. doi: 10.1109/TIE.2021.3094478
- Zhang, Y., Wang, X., Peng, J., Kong, L., Wang, Z. and Mao, Y. (2025). Fault Diagnosis and Adaptive Fault-Tolerant Control of Interturn Short-Circuit Fault in PMSM Drives. *IEEE Transactions on Instrumentation and Measurement*, 74, pp. 1–11. doi: 10.1109/TIM.2025.3645891.
- Zhang, J., Zhan, W. and Ehsani, M. (2023). Diagnosis and Fault-Tolerant Control of Permanent Magnet Synchronous Motors With Interturn Short-Circuit Fault. *IEEE Transactions on Control Systems Technology*, 31(4), pp. 1909–1916. doi: 10.1109/TCST.2023.3239426
- Zhang, W., Xu, D., Enjeti, P. N., Li, H., Hawke, J. T. and Krishnamoorthy, H. S. (2014). Survey on Fault-Tolerant Techniques for Power Electronic Converters. *IEEE Transactions on Power Electronics*, 29(12), pp. 6319–6331. doi: 10.1109/TPEL.2014.2304561
- Zhiduan, C. and Lihao, X. (2024a). A unified SVPWM Fault Tolerant Control Algorithm for Single Leg Fault Reconstruction Topology of Two-Level Inverter. *Scientific Reports*, 14(1), p. 8819. <https://www.nature.com/articles/s41598-024-59425-5>. doi: 10.1038/s41598-024-59425-5
- Zhiduan, C. and Lihao, X. (2024b). A unified SVPWM Fault Tolerant Control Algorithm for Single Leg Fault Reconstruction Topology of Two-Level Inverter. *Scientific Reports*, 14(1), p. 8819. doi: 10.1038/s41598-024-59425-5
- Zhu, C., Zeng, Z. and Zhao, R. (2017). Comprehensive Analysis and Reduction of Torque Ripples in Three-Phase Four-Switch Inverter-Fed PMSM Drives Using Space Vector Pulse-Width Modulation. *IEEE Transactions on Power Electronics*, 32(7), pp. 5411–5424. doi: 10.1109/TPEL.2016.2605160